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Bubbling to turbulent bed regime transition of ternary particles in a gas–solid fluidized bed

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ABSTRACT

The transition from bubbling to turbulent flow regime of a wide particle size distribution (PSD) powder was investigated in a circulating fluidized bed riser with an internal diameter and a height of 0.1 and 3.7 m, respectively. Iron ore and limestone particles were used as the wide PSD powder. To study the effect of particle size distribution on the flow regime transition, five types of mono size glass bead were used. Binary and ternary mixtures were made from the mixture of mono size glass beads. The regime transition of the wide PSD powder was studied by means of overall pressure drop and pressure fluctuation analysis. By gradually increasing the superficial gas velocity, a bed of a wide PSD powder changed from a fixed bed state to partial fluidization and then to complete fluidization. The transition from bubbling to turbulent fluidization occurred in the complete fluidization state. The effects of fine particle concentration, coarse particle size, and particle size distribution on bubbling-to-turbulent regime transition velocity were also studied. A correlation expressed in terms of Re_c, Ar, and standard deviation of particle size distribution (σ_p) was proposed to predict the transition velocity (U_c). The predicted U_c values were in close agreement with the experimental data of mono, binary, and ternary mixtures.

1. Introduction

Particle size distribution (PSD) has a significant effect on the fluidized bed hydrodynamics and other bed characteristics. Narrow PSD powder improves the bed stability. Since the difference of maximum and minimum particle diameter is small, de-fluidization, segregation, and entrainment are reduced [1]. A wide PSD leads to better bed fluidity and chemical conversion. The improvement in bed fluidity is attributed to the fines acting as lubricants [2]. Moreover, broadening of the particle size distribution affects the gas flow through the dense phase, produces smaller bubbles, leads to more particles in the dilute phase, and causes an earlier transition to turbulent fluidized bed regime. Therefore, the chemical conversion is enhanced by broadening the PSD [3,4].

In general, fluidized bed processing of natural ores is not conducted with particles of narrow particle size distributions because grinding and sieving for size cutting are time and energy consuming. Therefore, wide PSD powders are usually used for economic reasons when processing ores and minerals [1]. One example is the iron making process. There are challenges when operating natural iron ore fluidized beds because more than 80% of the iron ore produced today is a mixture of fine Geldart group C particles and coarse group D particles [5]. At low gas velocities segregation of coarse particles can occur while excessive entrainment and loss of the fine materials can occur at high gas velocities. It is, therefore, necessary to study the flow regime transitions of wide PSD powders in order to determine the proper operating conditions of fluidized beds used in processing natural ores and minerals.

Often, industrial fluidized is operated in turbulent fluidized bed mode because they give vigorous gas–solid contacting, favorable bed-to-surface heat transfer rates, and higher chemical conversion [6]. When using a wide PSD powder as the raw material, it is necessary to determine the transition velocity (U_c), at which turbulent fluidization begins. Fluidized bed regime transition points are mostly established by the analysis of pressure fluctuations [7–14]. While many studies have looked at the effects of particle diameter, particle density, column diameter, bed height, and temperature on the bubbling-to-turbulent fluidization transition velocity, U_c, only a few have reported the effect of particle size distribution [3,4] on U_c.

The objective of this work was to determine the transition velocity from bubbling to turbulent fluidization regime for ternary particles with a wide particle size distribution. Tests were conducted with two types of natural iron ores and limestone mixtures. Additionally, tests were conducted with mono, binary and ternary glass bead mixtures to find out the effect of particle size distribution on U_c. A correlation to predict U_c for wide PSD powders has been proposed.

2. Historical background

Different measurement methods have been used for the determination of the transition from bubbling to turbulent fluidization such as visual observation, local capacitance, overall bed expansion and pressure fluctuations [6].

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Kehoe and Davidson [15] defined turbulent fluidization using visual observations as a state of “continuous coalescence”. Group A particle beds were found to have a sharp bubbling to turbulent regime transition while groups B and D had gradual transitions. Determination by visual observation can only be used in non-slugging systems with group A particles [16]. Groups B and D can have slugging.

Lanneau [17] defined “a heterogeneity index” based on the capacitance signals as half the average of absolute deviation of the local bed density from its mean value. This index first increases with increasing gas velocity, reaching a maximum value and then decreases. The gas velocity at which the index reached a maximum was considered to be the bubbling-to-turbulent fluidization transition point.

Avidan and Yerushalmi [18] observed a rapid change in bed voidage using capacitance probe when a flow regime transition occurs. They defined the transition velocity as the gas velocity at which an abrupt change occurred in the bed expansion. However, in fluidized beds where entrained particles are returned to the bed, such abrupt changes tend to disappear [3,10]; therefore, this method cannot be used in fluidized bed with a solids circulating loop.

In this study the superficial gas velocity at the transition from bubbling to turbulent fluidization was determined by the statistical analysis of absolute pressure fluctuations. In a bubbling bed, an increase in the standard deviation of the pressure fluctuations can be related to bubble growth through bubble coalescence. In the turbulent regime, the standard deviation decreases because of the breakdown of bubbles. For this reason, the gas velocity at which the standard deviation of pressure fluctuations reaches a maximum is taken as the transition from bubbling to turbulent fluidization [19].

3. Experimental

Experiments were conducted in a circulating fluidized bed unit shown in Fig. 1. The riser section of the fluidized bed was a cylindrical Plexiglas column with an internal diameter of 0.1 m and a height of 3.7 m with a cyclone installed on its top. The entrained solids were recycled by a downcomer through a loop seal that regulated solid circulation rate by aeration. Some loop seal air enters the riser, but its amount is negligible when compared to that of the main air stream. The gas distributor was a bubble cap of tuyere type containing 72 holes of 2 mm diameter with 13 mm-triangular pitches. The riser air supply line had a pressure regulator and a calibrated flow meter. The unit was electrically grounded to minimize electrostatic effects. The experiments were carried out with static bed heights of 0.4 to 0.45 m. Taps for the measurement of bed pressure drop in the riser were mounted flush with the wall of the column at 0.05 m (lower tap) and 3.6 m (upper tap) above the distributor. Absolute pressure fluctuation signals were measured at the axial location of 0.25 m above the distributor. Pressure taps were covered with a fine mesh (45 μm) to prevent solid ingress into the pressure transducer lines. The probes were connected to the differential pressure transducer by polyurethane tubings. For measurement of the absolute pressure fluctuations, the probe is connected to high pressure, differential pressure transducers. The output signals were acquired by a personal computer at a sampling frequency of 50 Hz for measurement periods of 50 s.

The wide PSD powders used in this study were two types of iron ore (pellet feed and sinter feed) and limestone. Pellet feed was a fine iron ore with a mean particle size of 48 μm. Sinter feed was a coarse iron ore. There were three types of sinter feeds with particle size ranges 0–2000, 250–2000 and 5000–2000 μm. The limestone particles had a 0–2000 μm size range. The particle densities of the pellet feed, sinter feed and limestone were 4479, 4200 and 2588 kg/m^3, respectively (Fig. 2). Pellet feed, sinter feed and limestone were used to formulate the three ternary mixtures tested in this work. Other details of the mixtures are given in Table 1. Glass bead mixtures were used to study the effect of the PSD on the transition velocity, U_c. The mono size particles used to formulate the glass beads had mean particle sizes of 268, 700, 900, 1100 and 1300 μm as shown in Table 2. Their particle density was 2500 kg/m^3 (Table 2). The binary and ternary mixtures were prepared by mixing these glass beads. The composition and properties of the binary and ternary glass bead mixtures are given in Table 3.

4. Results and discussion

4.1. Overall flow regime transition of wide PSD powders (ternary mixture)

Previous studies on minimum fluidization velocity [1] have shown that the pressure drop versus gas velocity graph of a bed of a narrow particle size distribution material differs significantly from that of a bed of a wide PSD material. The $-\Delta P$ vs. Ug graph of a bed of a narrow PSD material has only one break point, which is at the minimum fluidization velocity, U_{mf}. In contrast, the transition from a fixed bed to a fluidized bed of a wide PSD material occurs gradually and two characteristics can be identified. The first is the incipient fluidization velocity, U_{if}, and the other is the one corresponding to the condition when all the particles become fluidized, the complete fluidization velocity, U_{cf}.

Fig. 3 shows the profiles of pressure drop across the bed and the standard deviation of the pressure drop fluctuations for the Ternary 1(1) solids mixture. Ternary 1(1) consisted of 81.9% sinter feed, 9.1% pellet feed and 9% limestone. The solids in the bed were initially well mixed. The total pressure drop curve for increasing gas velocity is significantly different from that of the decreasing gas velocity. Commonly, in the case of increasing gas velocity, whole bed of wide PSD powder undergoes different fluidization regimes (fixed bed, partial fluidized bed, complete fluidized bed). In this study, these regimes were detected based on visual observation and pressure data. The incipient fluidization point, U_{if}, for Ternary 1(1) solids mixture was not identifiable. Also, the fixed bed pressure drop did not rise quite linearly with increasing gas velocity. It appears that the ultra-fine particles in the size cut of 19 μm (0–38 μm) particles started to fluidize under a very low gas velocity (around 0.0097 m/s). What is occurring can be described as follows. As the gas velocity is increased, the fine particles in the mixture start to fluidize first while the coarse particles remain in a fixed bed state. In the partial fluidized bed, the measured total pressure drop begins to increase and decrease repeatedly because the fine particles start to move up and down in the interspace of the coarse particles even though the coarse particles remain in a fixed bed state [20]. As the gas velocity is further raised, the fine particles form a fluidized bed layer on top of a fixed bed layer of coarse particles. So, there is a top fluidized region and a bottom fixed region. As the gas velocity is raised, the height of the top fluidized region increases because more particles became fluidized and that of the bottom fixed region decreased. The standard deviation of pressure fluctuations increases linearly with increasing gas velocity suggesting that the partially fluidized bed region is transiting to the bubbling fluidization regime. Inspecting the increasing gas velocity curve (solid circle), a gas velocity is reached at which the pressure drop reaches a maximum value and then it decreases linearly with increasing gas velocity. The reason for the decrease is likely due to significant amounts of the fine solid particles that were entrained and circulated through loop seal. If particles were not entrained, the total pressure would not drop but would remain nearly constant with further increasing of the gas velocity. Conventionally [1,21], complete fluidization point, U_{cf}, is taken as the gas velocity at which the pressure drop starts to become constant. However, in this study, there was no leveling off in the pressure drop because of the entrained particles. The complete fluidization point was therefore defined as the gas velocity at the peak pressure drop from the increasing gas velocity curve. Visual observation confirmed that the bed was wholly fluidized. Above U_{cf}, the standard deviation of the pressure fluctuations continued to increase with increasing gas velocity until it reached a peak and then started to decrease steadily after that. The gas velocity corresponding to the peak standard deviation of pressure fluctuations was taken to be U_c, the start of transition from bubbling to turbulent fluidization. With the decreasing gas